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Climate for crops: integrating climate data with information about soils and crop requirements to reduce risks in agricultural decision-making

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Locally applicable information about climate and soil properties can help farmers identify opportunities and reduce risks associated with changing to new land uses. This article describes techniques for preparing high-resolution regional maps and GIS surfaces of agriculturally relevant climate parameters. Ways of combining these climate surfaces with soil data and information about the physical requirements of crops to identify areas likely to be the most suitable for new high-value crops are then outlined. Innovative features include methods for merging observations from temporary climate stations installed for one to two years in conjunction with longer-term climate station observations to improve input data for the maps, and techniques for mapping quantiles of climatic factors that may constrain agricultural operations. Examples are the expected 'one-in-five year' first and last frost dates, and the 'one-in-five year' lowest and highest seasonal rainfalls. The use of night-time satellite infrared observations to improve spatial resolution of frost hazard maps is also described. Typical standard errors of these climate mapping techniques are summarised. The benefits of ongoing consultation with local farmers and local government staff during the design and implementation of climate/soil/crop potential studies are described. These include optimising products to meet local needs, quality control of the resulting maps and GIS surfaces through local knowledge, and improved uptake of information by users. Further applications of techniques described in this paper include products useful to the energy sector, preparation of daily gridded climate data estimates for use in water quality and plant growth modelling, and development of regional climate change scenarios.

Keywords: agrometeorology, climate mapping, GIS, frost, rainfall, crop-climate relationships

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1. Introduction

In temperate latitudes there is continuing interest from farmers, land managers and investors as to whether they could successfully grow new high value crops (such as grapes, olives, berry fruit or flowers) on land presently used for activities such as pastoral agriculture. The economic success of changing to a new crop depends on a range of factors, including market demand, availability of processing, and transport infrastructure, and whether the climate, soil and terrain are suitable for the crop in question. Some of the climate and soil

constraints can be overcome, for example through use of fertiliser or through irrigation. Other factors such as inadequate growing-degree days, insufficient winter chilling, or risk of unseasonably heavy frosts can make particular crops marginal or uneconomic in certain regions.

This article outlines techniques applied in New Zealand for estimating and mapping climatic factors that can determine the suitability of a particular area for a selected crop. Such maps can also provide farmers with useful guidance on matters such as water requirements for irrigation, or the required level of frost protection. A method to combine this climate information in a GIS system with soil information and data about crop requirements in order to identify areas with the maximum potential and lowest risk for a particular crop is then discussed. Armed with such information, together with knowledge about market demand, farmers and their advisors can make rational estimates of the likely economic benefit from a change in land use. This information can also reduce the risk that farmers will try to grow a new crop in an area where the climate or soil is unsuitable.

The foundations for climate mapping work are well established. Atlases containing climate maps have been prepared for many parts of the world on many spatial scales (e.g. Auer et al. 2001; Daly et al. 2003; Leathwick et al. 2003b; NCDC 2002; Purdie et al. 1999). Many of the mapping techniques used have drawn on methods developed or applied by others (e.g. Hutchinson & Bischof 1983; Hutchinson 1989, 1991, 1995; Daly et al. 1994; Leathwick et al. 2003a). However, some innovations have been added. In particular, considerable effort has been put into developing climate quintile maps (e.g. the lowest summer rainfall or the latest frost date expected one year in five). This is because farmers have indicated that year-to-year climate variability can be as important as the long-term mean climate for determining whether a location is suitable for a particular crop.

Other developments include:

- improving spatial mapping of climate parameters in data sparse areas by installing temporary climate stations for one to two years;
- developing methods to utilise both short-term and long-term observation series in estimating and mapping climate quantiles;
- utilising night-time infrared satellite observations to improve estimates of frost risk;
- applying modern GIS software to combine climate information with relevant knowledge prepared by soil and crop scientists, and to deliver it to users in a readily accessible and understandable form; and
- mapping a comprehensive range of potentially limiting climate factors (e.g. seasonal rainfall quantiles, frost date quantiles, maximum annual wind speed, mean annual wind speed, potential evapotranspiration, solar radiation quantiles, soil temperature). These provide useful additions to the growing-degree day statistics that are often used for a first attempt at identifying the suitability of an area for a new crop (e.g. Hutchinson & McIntosh 2000).

The article also briefly describes the benefits of involving farmers and local government staff and councillors in the design, planning and execution of studies relating to climate, soil and crop potential.

2. Mapping climatic elements

Mid-latitude Southern Hemisphere westerlies and associated weather systems passing over New Zealand interact with the country's complex terrain to produce substantial spatial variations in the climate (Coulter 1975; Salinger et al. 2004). The National Climate Observing Network administered by NIWA (National Institute of Water and Atmospheric Research) currently comprises 208 climate stations and 654 rainfall observing sites. While this may seem a reasonable measurement density for a country of 286,000 square kilometres, simple spatial interpolation between these sites does not capture the complex climate variations over the intervening terrain.

Installing extra climate stations for a limited time can be helpful for mapping the climate of a limited area (such as that covered by one of New Zealand's 13 regional councils). However, availability of such data generates the extra challenge of merging short-term and long-term climate records. This is not trivial, since many parts of New Zealand experience year-to-year and decade-to-decade fluctuations in climate due to features such as the El Niño–Southern Oscillation and the Pacific Decadal Oscillation (Salinger et al. 2004).

Sections 2.1 and 2.2 outline methods for addressing these spatial and temporal challenges posed by climate mapping, which of course are present in many other countries as well as New Zealand. They describe spline fitting and statistical methodologies used to prepare data for mapping temperature, growing degree days, winter chilling, rainfall and potential evapotranspiration. Later sections outline methods used for mapping frost, wind, and solar radiation.

2.1. Filling the gaps: thin plate smoothing spline interpolation

To be useful for the purposes outlined in this article, climate information is needed with a spatial resolution of 1 km or better. This requires spatial interpolation of meteorological data from irregularly spaced climate stations onto high resolution regular grids, through a procedure which can reflect the main causes of between-station variability. Hutchinson (1991, 1995) describes the method of thin plate (or Laplacian) smoothing spline

interpolation and its application to the interpolation of climate data. This method is summarised in the following paragraphs.

Many standard interpolation packages use bivariate interpolation, or interpolation based on two variables (usually x and y location parameters, e.g. latitude and longitude). For example, inverse distance weighting (IDW) is an interpolation method that estimates values between locations using a weighted average of the data from those locations, where the weights are the inverse of the distance from the data sources to the interpolation point. Bivariate interpolation therefore requires detailed information about the location of the data sources (e.g. climate stations). However, these methods do not incorporate any dependencies on additional geographic variables, such as elevation, which are often highly significant. Thin plate smoothing splines provide a robust way of incorporating any number of additional variables that may improve the accuracy of the interpolation, in addition to location.

Most meteorological variables, such as air temperature, rainfall and evaporation, are affected by altitude. Thus, it makes sense to interpolate these parameters using a spline model with two position variables (latitude and longitude) and a linear dependence on elevation. The broad spatial pattern is determined by the two position variables, while the inclusion of elevation modifies the broad pattern to give more precise representations of the higher resolution variability. An advantage of the spline formulation is that the coefficient of the linear submodel (e.g. the temperature rate of change with elevation, or the lapse rate) is determined automatically from the data (Hutchinson 1991), and therefore does not need to be specified *a priori*. Additional geographic variables such as distance from the coast or proximity to the main divide, or meteorological variables such as cloud cover per cent (for mapping solar radiation) can also be included in the spline model.

A thin plate smoothing spline works by fitting a surface to the data with some error allowed at each data point, so the surface can be smoother than if the data were fitted exactly. A single parameter controls the smoothing and is normally chosen to minimise the mean square error between the actual value at the stations and their values predicted by all the other stations. That is, each station is omitted in turn from the estimation of the fitted surface and the mean error is found. This is repeated for a range of values of the smoothing parameter, and then the value that minimises the mean error is taken to give the optimum smoothing. This is called the method of generalised cross validation (GCV).

Hutchinson (1989) used a trivariate (three variable) thin plate smoothing spline to interpolate several meteorological variables across Australia. The number of data points varied according to the meteorological parameter; 150 points (i.e. climate stations) for solar radiation, 300 for pan evaporation, 900 for maximum and minimum air temperature, and 10,000 points for precipitation. The approximate standard errors calculated within the spline program for this Australian study were: solar radiation 3%; pan evaporation 5%; minimum and maximum temperature 0.2–0.5 °C, and rainfall 10–15%.

Table 1 shows the typical standard errors from the spline fitting procedure in a climate mapping project undertaken over the Otago Regional Council area, called 'growOTAGO'. The Otago region covers 32,000 square kilometres of New Zealand's South Island at approximately 46°S latitude, and ranges from coastal land to mountains up to 3000 m high. Annual rainfall in the high Alps can exceed 11 m (Wratt et al. 2000) while some of the dry inland rain shadow areas receive 36 cm or less of rainfall annually (Tait et al. 2001). For the purposes of this study, the national climate and rainfall station network was supplemented by full climate measurements at approximately 100 extra sites for a year or more, and extra air temperature observations were taken at a further 100 sites. (The method of incorporating these extra short-term measurements is outlined in the next section.)

2.2. The temporal challenge: merging short-term and long-term data to estimate climate percentiles

The quality of climate maps derived from the interpolation of station data is dependent on the density of long-term climate stations. For example, the mapped spline interpolation will capture the spatial variation of rainfall better in lowland areas where rainfall has been measured for many years from a dense network of rain gauges, than in upland areas where there are relatively few recording sites. Deploying additional climate stations to supplement an existing network is an obvious approach to improving the spatial representation of climate maps.

Because of the year-to-year variability in climate one would ideally operate such additional stations for many years, but this would be expensive and lead to undesirable delays in producing maps of long-term climate statistics. As a way around this, Sansom & Tait (2004) have developed a method for estimating long-term climate information at locations with shorter-term data records. Using their method, areas with a low density of climate stations can be augmented with temporary stations for short periods (e.g. one year), and after estimates of long-term statistics are made at these new sites, maps can be produced with improved accuracy.

Sansom & Tait's method is explained here for autumn temperatures, with reference to Figure 1. The method can also be used for other climate parameters, other seasons, or a full year. The first step is to determine the

Table 1. *Typical standard errors of climate mapping carried out for the Otago Regional Council area (Tait et al., 2004).*

Climate parameter	Lowland areas	Upland areas
Annual rainfall total	30–40 mm	70–90 mm
Seasonal rainfall total	10–20 mm	40–50 mm
2-monthly rainfall total	7–15 mm	30–40 mm
Annual number of rain days	4–6 days	8–10 days
Seasonal number of rain days	1.5–2.5 days	5–6 days
Seasonal 24-hour maximum rainfall total	2–5 mm	5–15 mm
Annual air temperature	0.3–0.5 °C	0.3–0.5 °C
Seasonal air temperature	0.3–0.5 °C	0.3–0.5 °C
Annual number of days with $T > 25\,°C$	1.5–3.5 days	0.5–1.0 days
Annual growing degree days (base 10 °C)	35–45 GDDs	10–20 GDDs
Annual growing degree days (base 5 °C)	60–70 GDDs	30–40 GDDs
Frost-free period*	26–28 days	26–28 days
Number of frosts in Sept, Oct and Nov*	0.6–0.8	0.6–0.8
First and last frost date*	10–20 days	10–20 days
2-monthly potential evapotranspiration	7–9 mm	6–8 mm
Annual wind speed*	4–5 km/hr	7–8 km/hr
Annual maximum wind speed*	15–18 km/hr	30–35 km/hr
Annual solar radiation*	0.6–1.0 $M\,Jm^{-2}\,day^{-1}$	0.6–1.0 $M\,Jm^{-2}\,day^{-1}$
Seasonal solar radiation*	0.6–1.0 $M\,Jm^{-2}\,day^{-1}$	0.6–1.0 $M\,Jm^{-2}\,day^{-1}$
Cool season chilling	65–80 hours	90–110 hours
Annual soil temperature	0.4–0.6 °C	0.4–0.6 °C
Seasonal soil temperature	0.4–0.6 °C	0.4–0.6 °C

Note: Spline fitting was used to map all of the parameters except for those indicated by an asterisk, for which the methods are briefly outlined in Sections 2.3 and 2.4. 'Upland areas' refer to terrain above about 500 m, where there are fewer observations.

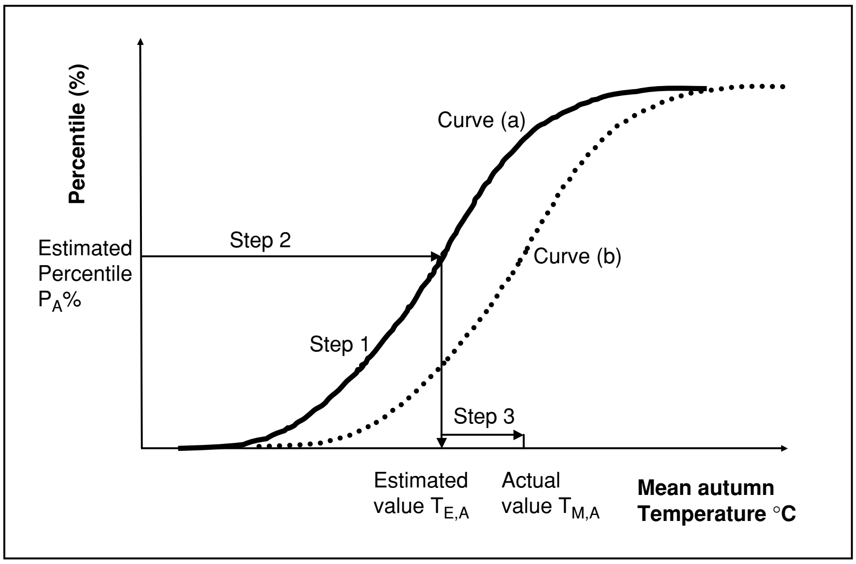

Figure 1. *Estimating a long-term seasonal temperature percentile curve for a short-term measurement site. The explanation is provided in the main text.*

deciles (minimum, 10th percentile, 20th percentile, ...) of the autumn mean temperatures at each of the climate stations with long-term records in the region to be mapped, over a period such as 30 years. Thin plate smoothing splines are then used to model the spatial variation of each of these decile values (for details see Sansom & Tait 2004). From these fits an estimated set of deciles was produced for each short-term station site. Curve (a) in Figure 1 is a percentile curve for one such site (site A), based on these estimated deciles.

The second step is to use the measured mean autumn temperature at each of the long-term stations for the particular autumn in which the short-term measurements were taken, to determine the actual value of the temperature percentile for this autumn at each of the long-term stations. A thin plate smoothing spline is then fitted to this set of autumn percentile values, and used to estimate the temperature percentile value for this particular autumn at each of the short-term measurement sites. Suppose that for site A this percentile is P_A%

(see Figure 1). The mean autumn temperature $T_{E,A}$ at site A corresponding to P_A% is then estimated using percentile curve (a).

An actual measured mean autumn temperature $T_{M,A}$ is also available at short-term site A for this autumn. The third and final step is to move the estimated percentile curve (a) for site A horizontally by an amount ($T_{M,A}$–$T_{E,A}$) to give curve (b). Curve (b) is the final estimated percentile curve for short-term site A, for the full period for which the long-term station deciles were calculated in step 1. Point values (for example, median temperatures, or 20th percentile temperatures) for use in preparing the climate maps are then obtained from these curves (for the temporary stations) and for the actual percentile curves from the long-term stations prepared under step 1.

Sansom & Tait (2004) showed that for the South Island of New Zealand this percentile-adjusted spline method generally performed better than a regression-based method for estimating long-term statistics at stations with short observation periods. They found that for the South Island the mean absolute error using this method is approximately 0.3 °C for air temperature, and 10% for rainfall. These errors are similar to the interpolation standard errors for these variables.

Sansom & Tait (2004) also demonstrate that regarding short-term station deployment, the better strategy is to have stations at sites for only one year and then move them to other sites rather than to have them at fewer sites for more than a year. This might well be expected since it ensures that the climate will have been sampled over the widest possible area. However, the above method depends on the existence of an adequate network of long-term stations. A decision must be made concerning the period from which to select the long-term climate station data. This becomes the period for which the derived climate maps are representative. For the 'growOTAGO' project we used a standard WMO 'normal' period (1971–2000).

A further point is that if the tails of the 'curve (a)' distribution are poorly defined for some reason (e.g. if the long-term period is substantially less than 30 years), and if the season or year in which the short-term record is obtained also exhibits extreme conditions, then the adjustment will be made near one of the tails of the distribution with a corresponding increase in error. In such a case consideration could usefully be given to running the short-term station for an extra year.

2.3. Frost risk: utilising surface and satellite observations

Interpolating climate station data using a spline model is often not as satisfactory for climate parameters that are strongly affected by non-localised influences. For example, frosts are affected by cold air drainage from surrounding terrain and pooling, and winds are influenced by chanelling, sheltering or speed up over surrounding terrain. Rather than use a spline interpolation, Tait & Zheng (2003) have developed a method for mapping frost incidence (i.e. the dates of the first and last frosts of the year) using a combination of climate station minimum air temperature data and night-time infrared radiance data from National Oceanic and Atmospheric Administration (NOAA) weather satellites.

The infrared satellite data are obtained for several cold cloud-free winter nights for the region of interest and the average of these winter radiances at the climate station locations are statistically related to the average date of the first and last air frosts at the stations. These dates are the dates when the minimum air temperature first measures less than 0 °C (first frost) and when the minimum air temperature last measures less than 0 °C (last frost). The regression relationship developed at the station locations is then applied to the spatially complete satellite data to estimate first and last frost dates over the whole area.

2.4. Wind mapping: utilising a physically-based model

Wind can vary significantly over short distances due to sheltering. Also, in hilly places wind flow is strongly related to land form. Observation networks in New Zealand do not have the resolution to allow the use of thin plate smoothing splines to map wind variations on the scale of individual hills. Instead, physically based models, which have the advantage of simulating the direct effects of the forcing by hills of winds over them, have been used. Details of the wind field can then be estimated at the resolution of the terrain data.

For the 'growOTAGO' project wind speeds were mapped using the WAsP (Wind Atlas Analysis and Application Program) wind flow model developed in Denmark (Troen et al. 1987). WAsP is based on mathematical approximations to the physical laws of mass and momentum conservation. As land height contours guide the flow of air over the land surface, the model determines how the speed varies from point to point.

The meteorological information used for the WAsP analysis was time series of hourly wind speed measurements from four long-term Otago wind measurement sites. Otago was broken in to a set of subregions. For each subregion the time series for the most appropriate of the four long-term anemometer locations (or a linear combination if there was more than one appropriate site) was adjusted for altitude above sea level following a relationship developed from an analysis of the denser short-term 'growOTAGO' anemometer network, and used as input for the WAsP analysis.

WAsP has been applied previously in New Zealand to windy areas with a high potential for wind power, and some limitations on its use have been noted in areas where winds are channelled (Reid 1997). Much of the terrain of Otago is suitable for modelling using WAsP. However, in some parts of the region the large horizontal and vertical scales of the hills almost certainly have physical effects beyond the model capabilities and the results should be used with caution.

2.5. Solar radiation mapping: a semi-empirical approach

It is possible to use a spline approach for creating solar radiation surfaces, e.g. Hutchinson et al. (1984); however, this approach tended to over-smooth the data. In the 'growOTAGO' project an alternative, empirical approach was used, based around the program SRAD (Moore et al. 1993).

In this approach a series of parameters is required: slope, aspect and elevation from the terrain model; a cloudiness surface; an albedo surface; various atmospheric transparency terms; and the proportion of diffuse radiation. Starting with the solar constant, time of year and surface position, each term is used to refine the estimate of the quantity of direct and diffuse radiation that reaches the surface. The terrain model is then used to better estimate the absolute quantity of solar radiation received at each point and to modify the quantity of direct radiation received, depending upon the slope and aspect.

Calculation of diffuse radiation requires an estimation of mean cloudiness across the region being mapped, together with an estimate of solar radiation on cloudy days. Cloudiness was based on the proportion of observed hours of bright sunshine to maximum possible hours of bright sunshine. Observed hours of bright sunshine were obtained from climate stations across the region, and maximum possible hours were calculated for each climate station. A cloudiness surface was then developed for the region to be mapped, using these ratios of observed/maximum sunshine at climate stations together with rainfall as a modifier, following the approach taken by Hutchinson et al. (1984). The radiation model was tuned using data from the local temporary climate stations. The final estimate at a location is a combination of the diffuse and the modified direct beam radiation.

2.6. Map design to aid interpretation

Applying appropriate technical procedures (spatial interpolation or modelling, temporal adjustments) is a necessary but not sufficient part of producing a useful climate map. Farmers and other users are most likely to use such maps if they are easy to understand and attractive to look at. Feedback from users in New Zealand has identified the importance of intuitive colour schemes (for example, blue for cold ranging to orange or red for warm). Some people have difficulty identifying shades of colour so it is useful to also include labelled contour lines. Adding roads, streams and terrain shading assists users in locating particular places of interest.

The availability of digital terrain surfaces, road and river layers in many countries, and the facilities available in standard GIS packages, make it relatively easy to provide these features. Figure 2 shows the detail of part of a median frost-free period map from the 'growOTAGO' project illustrating many of these matters. The full version of the map (Figure 3) is printed for users at 1:50,000 and covers an area 40 km by 30 km. Printable paper maps have been organised to cover exactly the same geographical areas as the standard New Zealand 1:50,000 topographical map series.

3. Soil and terrain information and crop requirements

For New Zealand, as for other temperate latitude developed countries, a large amount of information has been gathered about soils and terrain (Leathwick et al. 2003a). Nevertheless, the type of information available and the level of spatial detail vary across the country, generally being more comprehensive for productive lowland areas than for remote high country. If there is insufficient spatial detail of soil information in some areas where farmers are interested in new crop options, the simplest solution is for a pedologist to undertake a soil survey in that area using standard techniques. This was done in some parts of Otago during the 'growOTAGO' project.

Projects undertaken for various local government organisations in New Zealand have included provision of maps or GIS layers for the following soil and terrain properties relevant to assessing suitability of areas for particular crops: soil terrains; soil series, types and phases; slope class; subsoil acidity; potential rooting depth; soil drainage class; profile available water; natural soil fertility. Further descriptions of these layers are provided by Griffiths et al. (2003), Tait et al. (2004) and Hewitt (1998).

Identifying the climate and soil factors known to be important for successful cultivation of a particular crop is the domain of horticultural and crop scientists. Such scientists can draw on literature searches, crop databases, and information about other regions where a particular crop is grown successfully. The approach we have taken is to identify optimal, marginal and unsuitable ranges for each limiting factor. For example, one of the potential tree crops considered in a study for the Kaipara and Far North District Councils in the northern North Island is fig. Ranges established for the extreme minimum air temperature criterion for fig trees are: optimal – warmer than zero degrees (no air frosts);

Figure 2. *An example of the detail from a grow*OTAGO*' median frost-free period map. Each grid square is 1 km by 1 km. The labels on the contours represent the median length of the annual frost-free period in days. (Reproduced courtesy of Otago Regional Council.)*

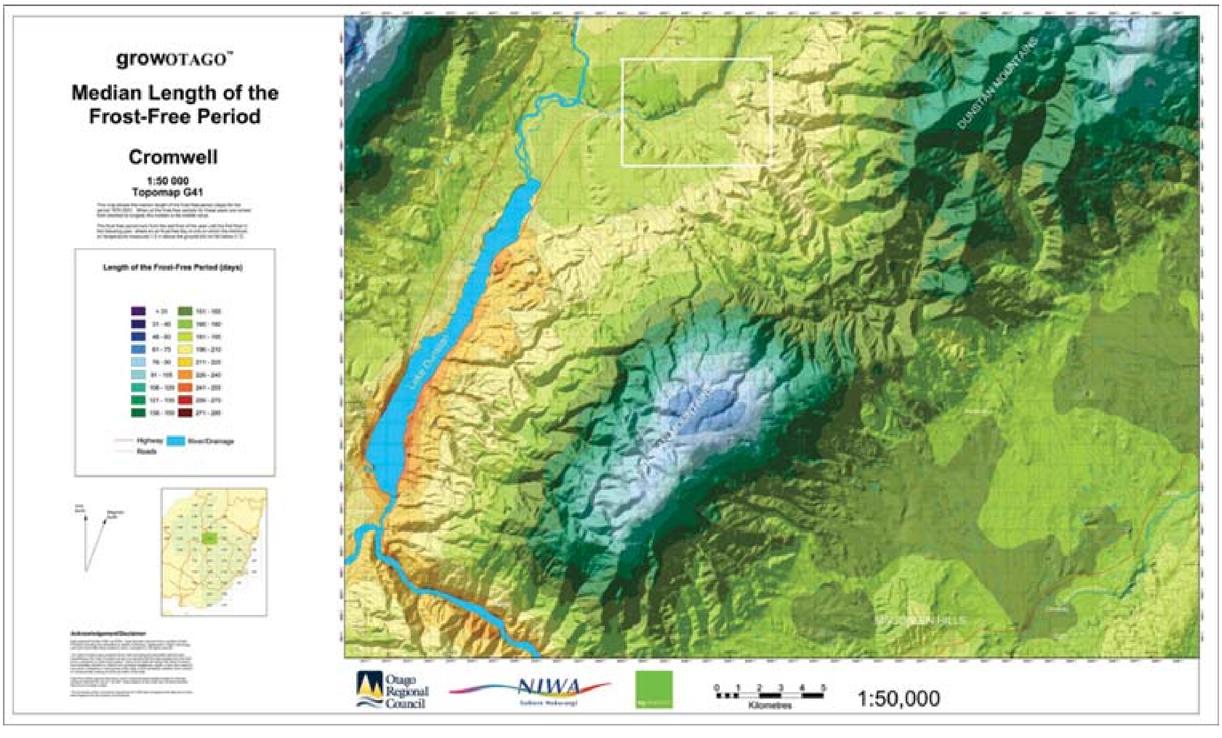

Figure 3. *The full layout of the map for which the detail for the small area delineated by the white rectangle is illustrated in Figure 2. (Reproduced courtesy of Otago Regional Council.)*

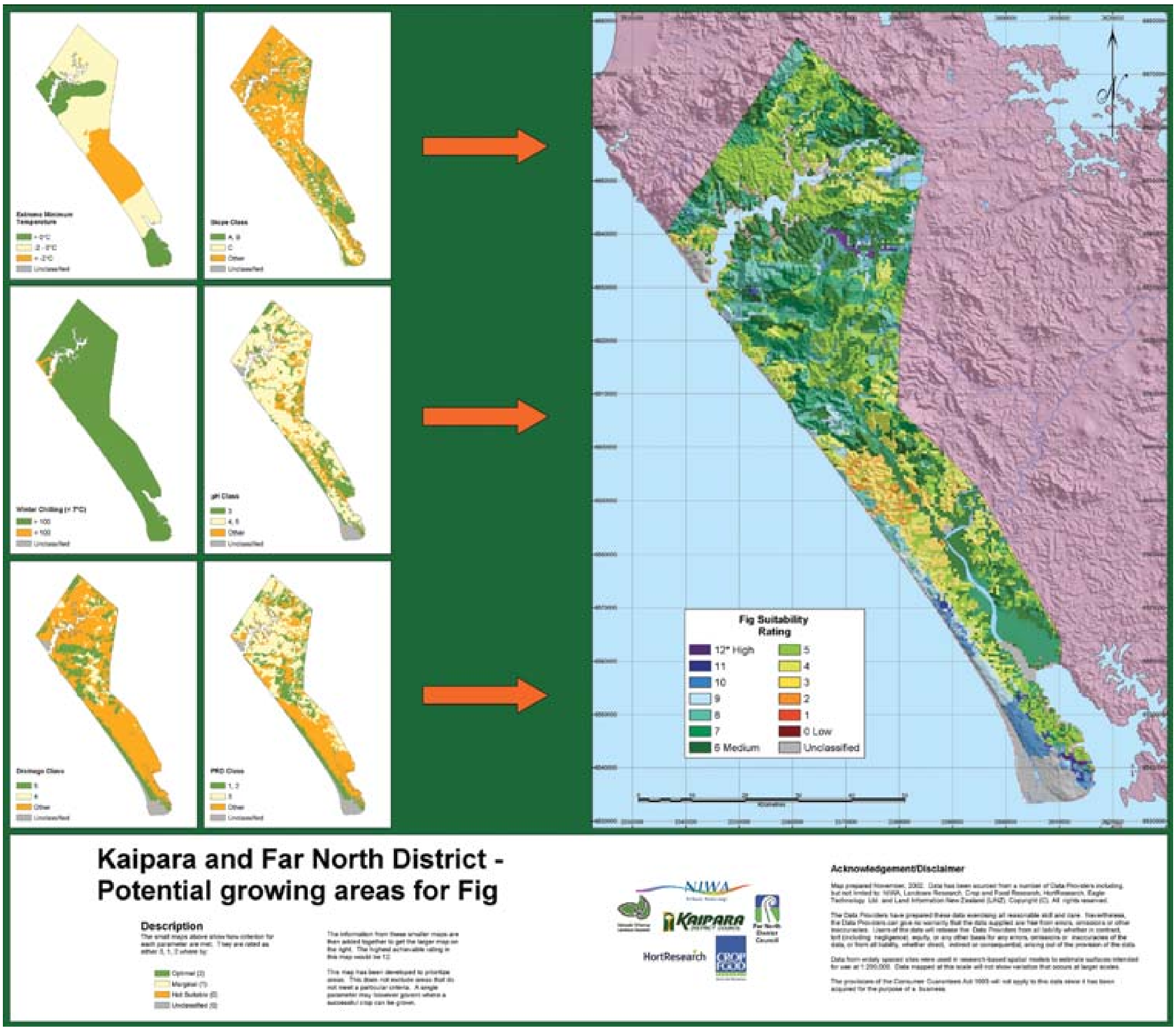

Figure 4. *Example of a 'potential growing area' map, for fig in part of the upper North Island of New Zealand. The six individual maps on the left show (clockwise, from top left) 'suitability indices' for extreme minimum temperature, slope class, soil pH, potential rooting depth, drainage class, and winter chilling. (Reproduced courtesy of Kaipara District Council and Far North District Council.).*

marginal – extreme minimum temperatures fall to between 0 °C and −2 °C; unsuitable – cooler than −2 °C.

4. Integrating climate, soil and crop information

As described in the previous section, agricultural scientists can be requested to provide optimal, marginal and unsuitable ranges for various climate, soil and terrain factors that are potentially limiting for a particular crop. For each of these factors, maps indicating the optimal, marginal and unsuitable areas can be prepared from the interpolated climate layers and the soil layers produced as outlined in Sections 2 and 3. Each of these individual 'suitability maps' can then be overlaid within a GIS to show the areas likely to be most and least suitable for the crop in question.

Figure 4 is an example of this approach, again looking at factors determining suitability for cultivation of fig trees. The individual smaller maps on the left show the suitability level under various criteria, with green indicating optimal, light yellow indicating marginal, and orange not suitable. For one of these individual maps, each underlying pixel or polygon is allocated the value of 0, 1 or 2 depending on whether it is classified as not suitable, marginal or optimum. These values are then summed over all six maps to provide a value between 0 and 12, which is then colour coded and used to produce the larger 'crop suitability' map on the right. Here the colour used for a score of 12 (purple) represents the most suitable regions, and colours representing high (but not perfect) scores indicate areas that may also be worth investigating.

The approach outlined here is a simple and transparent way of integrating climate and soil information, which is readily understood by users. However it does suffer from the drawback that any 'global limiters' are not strongly identified in the large right-hand map. For

example there are places in Figure 4 that show a relatively high (green) fig suitability rating, but where the soil drainage class is deemed as unsuitable (coloured orange in the left hand side drainage map). Such areas might not be suitable without site modification (e.g. drainage), since figs are quite susceptible to 'wet feet'. An alternative approach is to give a very low overall score or to mask out areas subject to such 'global limiters'. This was decided against, since some limiters can potentially be addressed by mitigation activities (e.g. installing drainage, providing frost protection). Nevertheless, viewing the information contained in the left hand side maps is very important, as well as considering the map on the right.

It is also very useful for farmers considering moving into new crops to have access to the underlying climate and soil maps described in Sections 2 and 3. For example, Riesling grapes are one of the horticultural crops for which we have prepared 'crop suitability maps' in some parts of New Zealand. To evaluate needs for frost protection or irrigation systems when establishing a vineyard, the farmer can examine the 'one-in-five-year' earliest and latest frost date maps, the seasonal potential evapotranspiration map, and the 'one-in-five-year' lowest seasonal rainfall map.

While the information illustrated in Figures 2, 3 and 4 has been described here in the form of conventional paper maps, it is often desirable to deliver the graphical information to users through the internet or on a CD. The availability of web server software that interfaces seamlessly with GIS software, and of browsers which can run on a PC to view GIS products on a CD or through the web, makes development of such web and CD products relatively straightforward.

5. The human dimension: involvement, infrastructure and markets

The goal of studies of climate, soil and crop potential, such as those described here, is their acceptance and uptake by farmers and planners. Involving local government staff, councillors and farmers in consultation and feedback throughout project planning and implementation is essential for good uptake of the products. This ensures that maps and delivery mechanisms are designed to meet local information needs. Consultation with local farmers eases installation of temporary climate stations, and their feedback, based on their very useful local knowledge, provides independent quality control of the maps.

This consultation can usefully extend beyond the climate and soil mapping. For example, in the Kaipara/Far North project (see Figure 4) the agricultural scientists in the project attended several local meetings to agree on a set of new, high-value crops for which crop potential maps would be produced. The booklet produced as one of the products of this study (Griffiths et al. 2003) compiled information about the market potential, cultivation, and infrastructure requirements for these crops, as well as providing background for interpreting the climate and soil maps.

6. Discussion and conclusions

6.1. Achievements and limitations of the methodology

In the past, farmers in New Zealand who wanted information about their local climate often had to make do with a climate summary from the nearest station in the NIWA climate network, perhaps with added verbal advice from a climatologist on how applicable this was to their own location. The information provided through the techniques described in this article represents a major step forward.

However, these techniques cannot provide perfect detailed information on climate elements that vary significantly on fine spatial scales due to very local effects. A good example is frost severity. The state of an air mass covering a region, and the absence of cloudiness (which allows strong radiational cooling) are important regional-scale influences on frost severity. So also is cold air drainage, mechanical mixing of cold air with warmer air further aloft due to turbulence generated by down-valley flow passing over trees and structures, and local terrain cover (which influences the emissivity of radiation). The use of satellite infrared data assists with picking out some of the broader-scale features resulting from these local processes. However, it cannot pick out some of the features that occur at scales of tens-to-hundreds of metres.

One way for a farmer considering a major investment (such as development of a vineyard) to obtain this very local information is to install a temperature measuring station right on site for 1–2 years. Techniques such as those described in Section 2.2 can be used on the resulting short-term data series to produce a 'synthetic' long-term climatology for assessing local frost risk. Similarly, a farmer who wants specific 'paddock-scale' information on local soils can purchase soil sampling and analysis services.

The climate maps (including quantile maps) produced by these techniques represent climate statistics for the period of long-term station data used (typically 30 years). However, the probabilities of frost or drought conditions occurring in particular years may depend on the state of certain large-scale climatic regimes, for example whether El Niño or La Niña conditions are present. For the 'growOTAGO' project we have addressed this issue by preparing separate rainfall maps for El Niño seasons and for La Niña seasons. The issue of possible future climate trends due to global climate change is addressed in the next subsection.

A further challenge for some crops is identifying the climate and soil constraints from the literature or from existing databases. Ecologists have developed systems that analyse the locations occupied by particular species to determine environmental constraints, and which then identify other areas with suitable environmental characteristics (e.g. Busby 1991; Carpenter et al. 1993; Mitchell 1991). It is planned to explore this option for some agricultural and horticultural crops in New Zealand.

6.2. Further applications

This article has focused on the use of climate mapping as an input to agricultural land-use decisions. However, the resulting maps and GIS surfaces have many other uses. For example, GIS surfaces of the 95th and 99th percentile of atmospheric temperatures developed using a spline fit to measurements from the national long-term climate network have been used by a company that runs high voltage networks transmitting electricity around New Zealand. These temperatures constrain the current that can be sent down individual transmission lines. Wind maps are of interest to companies evaluating the wind energy potential of various sites. Maps of seasonal snow-water equivalent are also of interest and have been produced (Tait et al. 2004) using the 'SnowSim model' developed at the University of Otago (Fitzharris & Garr 1995; Fitzharris & McAlevey 1999).

The thin plate smoothing spline interpolation methods outlined in Section 2.1 can also be applied to daily data sets, to produce a gridded data set of estimated daily values. Gridded estimated historical (30-year) daily data sets of maximum and minimum temperature, rainfall, saturation deficit, and potential evapotranspiration on a 0.05° latitude/longitude grid (approximately 4 km) over New Zealand have been prepared, and it is planned to extend this to solar radiation and wind. Scientists are using these data sets to develop and test models of river water quality, ground water recharge, and grass growth and dairy production.

Both national and regional governments are currently interested in identifying potential effects of climate change, in order explore adaptation options. GIS climate parameter surfaces developed following the procedures outlined in Sections 2.1 and 2.2, or the gridded daily climate surfaces described in the previous paragraph, can be offset according to regional downscaled climate projections corresponding to various IPCC greenhouse gas emission scenarios (Wratt et al. 2004). This provides a set of 'what-if' climate change scenarios available for regional impact studies, which can be used in a similar way to the coarser-scale regional projections developed for the CLIMPACTS integrated assessment model (Kenny et al. 2000).

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